4 Newton's First Law of Motion—Inertia

Chapter 4 extends the previous coverage of motion, and centers on the concept of inertia. Velocity vectors of the previous chapter are here extended to forces in a treatment of statics.

Because of its huge inertia, the ship is not easily pushed off course.

If you saw a boulder in the middle of a flat field suddenly begin to move across the ground, you'd look for the cause of its motion. You might look to see if someone was pulling the boulder with a rope or pushing it with a stick. You would reason that something was causing it to move. We don't believe that motion occurs without cause. In general, we say the cause of the boulder's motion is a force of some kind. We know that something forces the boulder to begin moving.

Videotape: Show "Newton's First Law" from the series *Conceptual Physics Alive!*

4.1 Aristotle on Motion

The idea that a force causes motion goes back to the fourth century B.C., when the Greeks were developing some of the ideas of science. Aristotle, the foremost Greek scientist, studied motion and divided it into two types: *natural motion* and *violent motion*.

Natural motion on the earth was thought to be either straight up or straight down, such as a boulder falling toward the ground or a puff of smoke rising in the air. Objects would seek their natural resting places: boulders on the ground and smoke high in the air like the clouds. It was "natural" for heavy things to fall and for very light things to rise. Aristotle proclaimed circular motion was natural for the heavens, for he saw both circular motion and the heavens as without beginning or end. Thus, the planets and stars moved in perfect circles about the earth. Since these motions were considered natural, they were not thought to be caused by forces.

Figure 4.1 ▲
Do boulders move without cause?

Violent motion, on the other hand, was imposed motion. It was the result of forces that pushed or pulled. A cart moved because it was pulled by a horse; a tug-of-war was won by pulling on a rope; a ship was pushed by the force of the wind. The important thing about defining violent motion was that it had an external cause. Violent motion

Many students still believe as Aristotle believed thousands of years ago. Although they can memorize, "In the absence of a force an object in motion tends

› stay in motion," many falla-
ously believe motion requires
ne presence of a force. This
elief is rooted in experience,
here in most cases a force
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was imparted to objects. Objects in their natural resting places could not move by themselves; they had to be pushed or pulled.

It was commonly thought for nearly 2000 years that if an object was moving "against its nature," then a force of some kind was responsible. Such motion was possible only because of an outside force. If there were no force there would be no motion (except in the vertical direction). So the proper state of objects was one of rest, unless they were being pushed or pulled, or were moving toward their natural resting place. Since most thinkers up to the sixteenth century considered it obvious that the earth must be in its natural resting place and assumed that a force large enough to move it was unthinkable, it was clear that the earth did not move.

4.2 Copernicus and the Moving Earth

It was in this intellectual climate that the astronomer Nicolaus Copernicus (1473–1543) formulated his theory of the moving earth. Copernicus reasoned that the simplest way to interpret astronomical observations was to assume that the earth (and other planets) move around the sun. This idea was extremely controversial at the time. People preferred to believe that the earth was at the center of the universe. Copernicus worked on his ideas in secret to escape persecution. In the last days of his life and at the urging of close friends, he sent his ideas to the printer. The first copy of his work, *De Revolutionibus*, reached him on the day of his death, May 24, 1543.

4.3 Galileo on Motion

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Galileo, the foremost scientist of late-Renaissance Italy, was outspoken in his support of Copernicus. As a result, he suffered a trial and house arrest. One of Galileo's great contributions to physics was demolishing the notion that a force is necessary to keep an object moving.

A **force** is any push or pull. **Friction** is the name given to the force that acts between materials that touch as they move past each other. Friction is caused by the irregularities in the surfaces of objects that are touching. Even very smooth surfaces have microscopic irregularities that obstruct motion. If friction were absent, a moving object would need no force whatever to remain in motion.

Galileo argued that only when friction is present—as it usually is—is a force needed to keep an object moving. He tested his idea by rolling balls along plane surfaces tilted at different angles. He noted that a ball rolling down such an inclined plane picks up speed, as shown on the left in Figure 4.2. The ball is rolling partly in the direction of the pull of the earth's gravity. He also noted that a ball rolling up an inclined plane—in a direction opposed by gravity—slows down, as shown in the center in Figure 4.2. What about a ball rolling

on a level surface, as shown on the right in Figure 4.2? While rolling level, the ball does not roll with or against gravity. Galileo found that a ball rolling on a smooth horizontal plane has almost constant velocity. He stated that if friction were entirely absent, a ball moving horizontally would move forever. No push or pull would be required to keep it moving once it is set in motion.

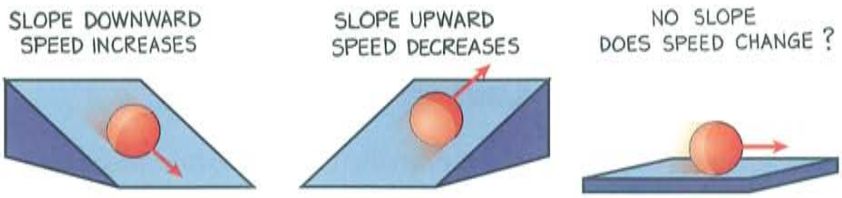

Figure 4.2
(Left) When the ball rolls downward, it moves with the earth's gravity and its speed increases. (Center) When the ball rolls upward, it moves against gravity and loses speed. (Right) When the ball rolls on a level plane, it does not move with or against gravity. Does the ball's speed change while rolling horizontally?

Galileo's conclusion was supported by another line of reasoning. He described two inclined planes facing each other, as in Figure 4.3. A ball released to roll down one plane would roll up the other to reach nearly the same height. The smoother the planes were, the more nearly equal would be the initial and final heights. He noted that the ball tended to attain the same height, even when the second plane was longer and inclined at a smaller angle than the first plane. In rolling to the same height, the ball had to roll farther. Additional reductions of the angle of the upward plane gave the same results. Always, the ball went farther and tended to reach the same height.

What if the angle of incline of the second plane were reduced to zero so that the plane was perfectly horizontal? How far would the ball roll? He realized that only friction would keep it from rolling forever. It was not the nature of the ball to come to rest as Aristotle had claimed. In the absence of friction, the moving ball would naturally keep moving. Galileo stated that every material object resists change to its state of motion. We call this resistance **inertia.**

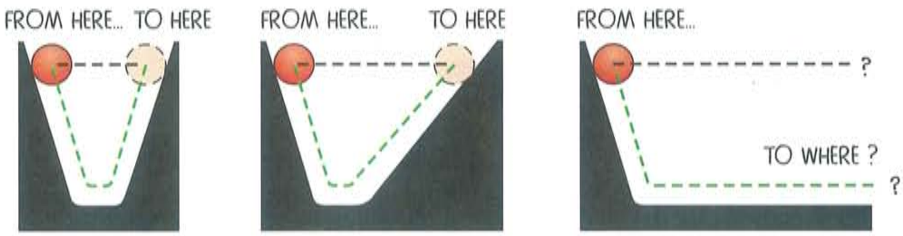

Figure 4.3
(Left) The ball rolling down the incline rolls up the opposite incline and reaches its initial height. (Center) As the angle of the upward incline is reduced, the ball rolls a greater distance before reaching its initial height. (Right) How far will the ball roll along the horizontal?

Galileo was concerned with *how* things move rather than *why* they move. He showed that experiment, not logic, is the best test of knowledge. Galileo's findings about motion and his concept of inertia discredited Aristotle's theory of motion. The way was open for Isaac Newton (1642–1727) to synthesize a new vision of the universe.

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Demo: Newton's Law of Inertia

Side 1
Chapter 16

The Best From Conceptual Physics Alive!

Demo: The Old Tablecloth Trick

Side 1
Chapter 17

■ **Question**

A ball is rolled across a counter top and rolls slowly to a stop. How would Aristotle interpret this behavior? How would Galileo interpret it? How would you interpret it?

4.4 Newton's Law of Inertia

On Christmas day in the year Galileo died, Isaac Newton was born. By age 24, he had developed his famous laws of motion. They replaced the Aristotelian ideas that dominated the thinking of the best minds for most of the previous 2000 years. This chapter covers the first of Newton's three laws of motion. Newton's two other laws of motion are covered in the following chapters.

Newton's first law, usually called the **law of inertia,** is a restatement of Galileo's idea.

> Every object continues in a state of rest, or of motion in a straight line at constant speed, unless it is compelled to change that state by forces exerted upon it.

Simply put, things tend to keep on doing what they're already doing. Dishes on a tabletop, for example, are in a state of rest. They tend to remain at rest, as is evidenced if you snap a tablecloth from beneath them. Try this at first with some unbreakable dishes. If you do it properly, you'll find the brief and small forces of friction are not significant enough to appreciably move the dishes (close inspection

Figure 4.4 ▲
Objects at rest tend to remain at rest.

Important Terms

law of inertia
Newton's first law

■ **Answer**

Aristotle would probably say that the ball stops because it seeks its natural state of rest. Galileo would probably say that the friction between the ball and the table overcomes the ball's natural tendency to continue rolling—overcomes the ball's inertia—and brings it to a stop. Only you can answer the last question!

will show that brief friction between the dishes and the fast-moving tablecloth starts the dishes moving, but immediately after the tablecloth is removed friction between the dishes and table stops them). Objects in a state of rest tend to remain at rest. Only a force will change that state.

Interactive Physics™ Simulations: 4 Rocket-Chair I, 5 Rocket-Chair II, 6 Grape Drop

Now consider an object in motion. If you slide a hockey puck along the surface of a city street, the puck quite soon comes to rest. If you slide it along ice, it slides for a longer distance. This is because the friction force is very small. If you slide it along an air table where friction is practically absent, it slides with no apparent loss in speed. We see that in the absence of forces, a moving object tends to move in a straight line indefinitely. Toss an object from a space station located in the vacuum of outer space, and the object will move forever. It will move by virtue of its own inertia.

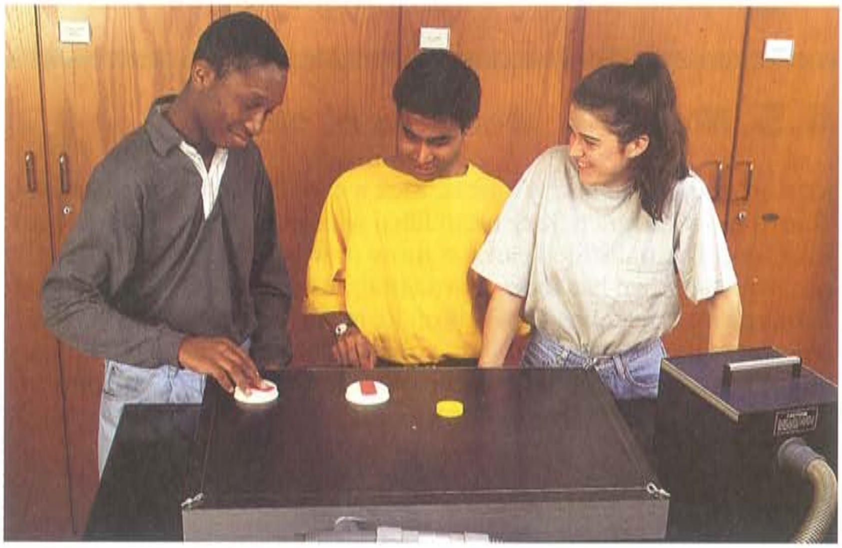

Figure 4.5
An air table: Blasts of air from many tiny holes provide a nearly friction-free surface.

Demonstrations for inertia: Balance a 3 × 5 card on your finger; flick it away with a hit from your other hand. Break the strings above and below the massive ball as shown in Think and Explain #6.

Pull the tablecloth beneath dishes on a table.

Examples of things in motion that tend to stay in motion: snow from shoes when stamped on the floor; dust on a coat that you shake

We see that the law of inertia provides a completely different way of viewing motion. Whereas the ancients thought continual forces were needed to maintain motion, we now know that objects

continue to move by themselves. Forces are needed to overcome any friction that may be present and to set objects in motion initially. Once the object is moving in a force-free environment, it will move in a straight line indefinitely. In the next chapter we'll see that forces are needed to accelerate objects, but not to maintain motion if there is no friction.

Questions

1. If the force of gravity between the sun and planets suddenly disappeared, what type of path would the planets follow?
2. Is it correct to say that the *reason* an object resists change and persists in its state of motion is that it has inertia?

4.5 Mass—A Measure of Inertia

Kick an empty can and it moves. Kick a can filled with sand and it doesn't move as much. Kick a can filled with steel nails and you'll hurt your foot. The nail-filled can has more inertia than the sand-filled can, which in turn has more inertia than the empty can. The amount of inertia an object has depends on its mass—which is roughly the amount of material present in the object. The more mass an object has, the greater its inertia and the more force it takes to change its state of motion. Mass is a measure of the inertia of an object.

Mass Is Not Volume

Do not confuse mass and volume. They are entirely different concepts. Volume is a measure of space and is measured in units such as cubic centimeters, cubic meters, and liters. Mass is measured in **kilograms.** If an object has a large mass, it may or may not have a large volume. For example, equal-size bags of cotton and nails may have equal volumes, but very unequal masses. How many kilograms of matter an object contains and how much space the object occupies

Answers

1. The planets would move in straight lines at constant speed—at constant velocity.
2. In a strict sense, no. We don't know the reason why objects persist in their motion when nothing acts on them, but we call this property *inertia*. We understand many things, and we have labels for these things. There are also many things we do not understand, and we have labels for these things too. Education consists not so much in acquiring new labels, but in learning what is understood, what is not—and why.

LINK TO SPACE SCIENCE

Inertia in Action

The spacecraft launched in the late 1970s on the *Pioneer* and *Voyager* missions have gone past the orbits of Saturn and Uranus and are still in motion. Initially, force supplied by rockets sent the spacecraft on their journeys. However, once in outer space these engines supplied no more force. Except for the gravitational effect of the stars and planets in the universe, do you see that the motion of the spacecraft will continue without change?

Figure 4.6 ▲
You can tell how much matter is in a can when you kick it.

Important Terms

kilogram
mass
newton
weight

are two different things. (A liter of milk, juice, or soda—anything that is mainly water—has a mass of about one kilogram.)

Which has more mass, a feather pillow or a common automobile battery? Clearly an automobile battery is more difficult to set into motion. This is evidence of the battery's greater inertia and hence its greater mass. The pillow may be bigger, that is, it may have a larger volume, but it has less mass. Mass is different from volume.

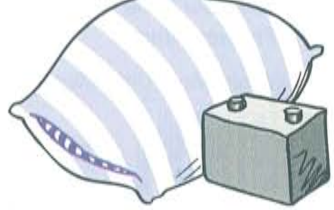

Figure 4.7 ▲
The pillow has a larger size (volume) but a smaller mass than the battery.

Mass Is Not Weight

Mass is often confused with weight. We say a heavy object contains a lot of matter. We often determine the amount of matter in an object by measuring its gravitational attraction to the earth. However, mass is more fundamental than weight. Mass is a measure of the amount of material in an object and depends only on the number of and kind of atoms that compose it. Weight on the other hand is a measure of the gravitational force acting on the object. Weight depends on an object's location.

The amount of material in a particular stone is the same whether the stone is located on the earth, on the moon, or in outer space. Hence, the stone's mass is the same in all of these locations. This could be demonstrated by shaking the stone back and forth in these three locations. The same force would be required to shake the stone with the same rhythm whether the stone was on the earth, on the moon, or in a force-free region of outer space. The stone's inertia, or mass, is solely a property of the stone and not its location.

Figure 4.8 ▲
It's just as difficult to shake a stone in its weightless state in space as it is in its weighted state on earth.

But the weight of the stone would be very different on the earth and on the moon, and still different in outer space. On the surface of the moon, the stone would have only one-sixth the weight it has on the earth. This is because the force of gravity on the moon is only one-sixth as strong as it is on the earth. If the stone were in a gravity-free region of space, its weight would be zero. Its mass, on the other hand, would not be zero. Mass is different from weight.

We can define mass and weight as follows:

> **Mass** is the quantity of matter in an object. More specifically, mass is a measure of the inertia, or "laziness," that an object exhibits in response to any effort made to start it, stop it, or otherwise change its state of motion.
>
> **Weight** is the force of gravity on an object.

While mass and weight are not the same thing, they are proportional to each other in a given place. Objects with great mass have great weight; objects with little mass have little weight. In the same location, twice the mass weighs twice as much. Mass and weight are proportional to each other, but they are not equal to each other. Remember that mass has to do with the amount of matter in the object, while weight has to do with how strongly that matter is attracted by gravity.

Even though *volume* is not a new word to your students, go over its meaning since many students misunderstand it.

Pass around class two objects that have about the same volume but extremely different masses—a lead brick and a concrete brick, for example. Have students shake both. This helps dispel the notion that mass is volume. Ask if they could tell the difference by shaking if they were orbiting in the space shuttle.

Force and mass are frequently used incorrectly in everyday life (e.g., weighing 3 kilograms), which contributes to confusion.

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Demo: Weight-Mass Distinction

Side 1
Chapter 20

Questions

1. Does a 2-kilogram iron block have twice as much *inertia* as a 1-kilogram block of iron? Twice as much *mass?* Twice as much *volume?* Twice as much *weight,* when weighed in the same location?
2. Does a 2-kilogram bunch of bananas have twice as much *inertia* as a 1-kilogram loaf of bread? Twice as much *mass?* Twice as much *volume?* Twice as much *weight,* when weighed in the same location?

One Kilogram Weighs 9.8 Newtons

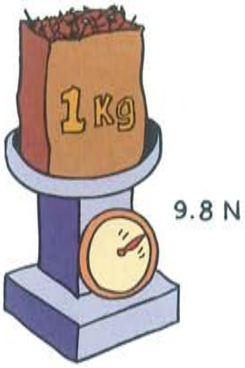

Figure 4.9 ▲
One kilogram of nails weighs 9.8 newtons, which is equal to 2.2 pounds.

In the United States it is common to describe the amount of matter in an object by its gravitational pull to the earth, that is, by its weight. In English-speaking countries, the traditional unit of weight is the pound. In most parts of the world, however, the measure of matter is commonly expressed in units of mass. The SI* unit of mass is the kilogram; its symbol is kg. At the earth's surface, a 1-kg bag of nails has a weight of 2.2 pounds.

The SI unit of *force* is the **newton** (named after guess who?). One newton is equal to slightly less than a quarter pound, about the weight of a quarter-pound burger *after* it is cooked. The SI symbol for the newton is N and is written with a capital letter because it is named after a person. A 1-kg bag of nails weighs 9.8 N in SI units. Away from the earth's surface, where the force of gravity is less, the bag of nails weighs less.

If you know the mass of something in kilograms and want its weight in newtons, multiply the number of kilograms by 9.8. Or, if you know the weight in newtons, divide by 9.8 and you'll have the mass in kilograms. Weight and mass are proportional to each other. *Weight* = *mass* × *acceleration due to gravity*, or simply, *weight* = *mg*.

The Best From Conceptual Physics Alive!

Definition of a Newton

Side 1
Chapter 22

Answers

1. The answer is yes to all questions. A 2-kilogram block of iron has twice as many iron atoms, and therefore twice the amount of matter, mass, and weight. The blocks are made of the same material, so the 2-kilogram block also has twice the volume.
2. Two kilograms of *anything* has twice the inertia and twice the mass of one kilogram of anything else. In the same location, where mass and weight are proportional, two kilograms of anything will weigh twice as much as one kilogram of anything. Except for volume, the answer to all the questions is yes. Volume and mass are proportional only when the materials are the same or when equal masses occupy the same volume, that is, when they have the same *density.* Bananas are much more dense than bread, so two kilograms of bananas must occupy less volume than one kilogram of bread.

* The metric system was originally established in France in the 1790s. The International System of Units (abbreviated SI, after the French name *Le Système International d'Unités*) is a revised version of the metric system. The short forms of the SI units are called *symbols* rather than *abbreviations.*

■ **Question**

The text states that a 1-kg bag of nails weighs 9.8 N at the earth's surface. Does 1 kg of yogurt also weigh 9.8 N at the earth's surface?

Important Term

net force

4.6 Net Force

In the absence of force, objects at rest stay at rest and objects in motion continue in motion. More specifically, in the absence of a *net force*, objects do not change their state of motion. For example, if you push with equal and opposite forces on opposite sides of an object at rest, it will remain at rest. The forces cancel each other out and there is no net force. The combination of all forces acting on an object is called the **net force.** It is the net force that changes an object's state of motion.

Figure 4.10 shows how forces combine to produce a net force. When you pull horizontally with a force of 10 N on an object resting on a frictionless surface, the net force acting on the object is 10 N. If a friend assists you and also pulls in the same direction with a force of 5 N, then the net force is the sum of these forces, or 15 N (Figure 4.10, top). The object moves as if it were pulled with a single 15-N force. However, if your friend pulls with a force of 5 N in the opposite direction, then the net force is the difference of these forces, or 5 N (Figure 4.10, center). The resulting motion of the object is the same as if it were pulled with a single 5-N force.

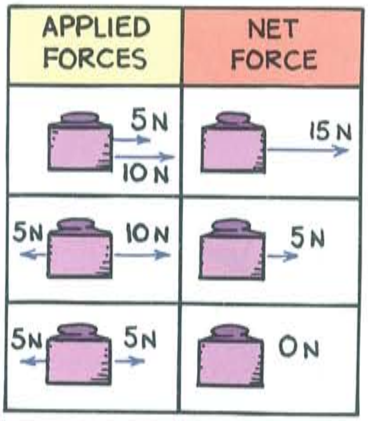

Figure 4.10 ▲
When more than one force acts on an object, the net force is the sum of the forces. When forces act in the same direction, the net force is the sum of the forces. When forces act in opposite directions, the net force is the difference of the forces.

4.7 Equilibrium—When Net Force Equals Zero

What forces act on your book while it is motionless on a table? Don't say just its weight. If only the force of gravity were acting on the book, it would be in free fall. The fact that the book is at rest is evidence that another force must be acting on it. This other force exactly balances the book's weight and produces a net force of zero. The other force is the **support force** of the table. Support force is often called **normal force.*** As shown in Figure 4.11, the table pushes up on the book with a force equal to the book's weight. When an

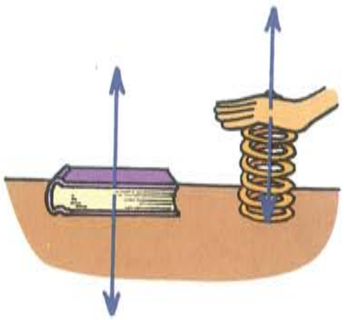

Figure 4.11 ▲
(Left) The table pushes up on the book with a force equal to the downward weight of the book. (Right) The spring pushes up on your hand with the same force you use to push down on the spring.

■ **Answer**

Yes, at the earth's surface 1 kg of anything weighs 9.8 N.

* This force acts at right angles to the surface. *Normal to* means "at right angles to," which is why the force is called a normal force.

Important Terms

equilibrium
normal force
support force

object is at rest, with the net force on it being zero, we say the object is in a state of **equilibrium.** The resting book is in equilibrium.

Does the table really push up on the book? Yes, just as a spring pushes up on your hand when you compress it. Look at Figure 4.11. You can feel the spring pushing back on your hand. Similarly, a book lying on a table compresses the atoms in the table. Behaving like microscopic springs, the atoms in contact with the book push back on it. Since the book is in equilibrium, the net force on it must be zero. The table actually pushes up on the book with the same force that the book presses down. An ant trapped between the book and the table would feel itself being squashed from both sides—the top and the bottom.

When you hang from a rope, the atoms in the rope are *not* compressed. Instead, the atoms are stretched apart. A tension force is established in the rope. A rope under tension "twangs" if you pluck it. How much tension is in the rope when you hang from it? If you are in equilibrium, then the tension must equal your weight. The rope pulls you up and the force of gravity pulls you down. Since the equal and opposite forces cancel each other, you hang motionless. Suppose you hang from a bar supported by two ropes, as in Figure 4.12. Neglecting the weight of the bar, the tension in each rope is one-half your weight. The total tension force acting upward ($\frac{1}{2}$ your weight + $\frac{1}{2}$ your weight) balances your weight, which acts downward. When doing pull-ups using both arms, each arm supports half of your weight. Have you ever tried pull-ups with just one arm? Why is it twice as difficult?

Figure 4.12 ▲
The sum of the rope tensions must equal your weight.

A spring scale can also be used to measure tension. When we weigh a bag of apples by suspending it on a spring, the scale reading tells us the weight. Consider a 1-kg bag of 10 apples weighing 10 N.

■ Question

When you step on a bathroom scale, the downward force supplied by your feet and the upward force supplied by the floor compress a calibrated spring. The compression of the spring gives your weight. In effect, the scale measures the floor's support force. What will each scale read if you stand on two scales with your weight divided equally between them? What happens if you stand with more of your weight on one foot than the other?

■ Answer

Since you are in equilibrium, the two scale readings must add up to your weight. The sum of the scale readings, which equals the support force of the floor, counteracts your weight so that the net force is zero. If you stand with your weight divided equally between the two scales, each scale will read half your weight. If you lean more on one scale, it will read more than half your weight. However, the two readings must still add up to your weight. For example, if one scale reads two-thirds of your weight, the other scale will read one-third of your weight. Get it?

When suspended by a single vertical scale as shown on the left in Figure 4.13, the scale reads 10 N. If instead we hang the 10-N bag from a pair of vertical scales as shown on the right in Figure 4.13, each scale reads 5 N. The two scales pull up with a combined force equaling the bag's weight, 10 N. Since the bag hangs at rest, the net force on it must be zero. The key concept is this: If a 10-N bag is in equilibrium, the *resultant of the forces* applied by the pair of springs must equal 10 N. If the spring scales are oriented vertically, this is easy: 5 N + 5 N = 10 N.

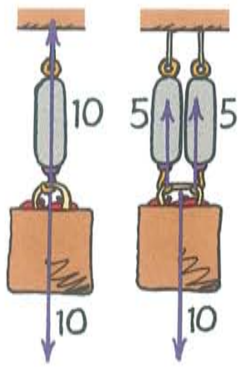

Figure 4.13 ▲
(Left) When a 10-N load hangs vertically from a single spring scale, the scale pulls upward with a force of 10 N. (Right) When the load hangs vertically from two spring scales, each scale pulls upward with a force equal to half of the load's weight, or 5 N.

4.8 Vector Addition of Forces

Let's now consider nonvertically oriented spring scales. The tension is greater in a pair of nonvertical spring scales and depends on their angle from the vertical. This more complicated situation is most easily understood using vectors. Recall our treatment of velocity vectors in Chapter 3. We'll now use the same vector addition techniques with forces. Force, like velocity, has magnitude and direction and is a vector quantity.

Relate inertia to projectiles covered in Chapter 3.

Look at the left of Figure 4.14. Notice that when the spring scales hang at 60° from the vertical, their readings are 10 N each—double the tension of the vertically hanging scales! Why? Because the sum of the two tension vectors must support the downward-acting 10-N weight. The sum of the vectors must be 10 N, directed vertically upward as shown by the diagonal of the parallelogram formed from the two vectors. For an angle 60° from the vertical, or 120° between the scales, 10 N of tension force is required in each scale. For angles greater than 60°, the scale readings would increase even more.

Notice that on the right of Figure 4.14, the angle from the vertical has increased to 75.5°. At this angle, each spring must pull with 20 N to produce the required 10-N vertically upward resultant. As the angle between the scales increases, the tension in the scales must increase for the resultant to remain 10 N. In terms of the parallelogram, as the scale's angle from the vertical increases, the magnitude of the tension force must also increase for the diagonal to remain the

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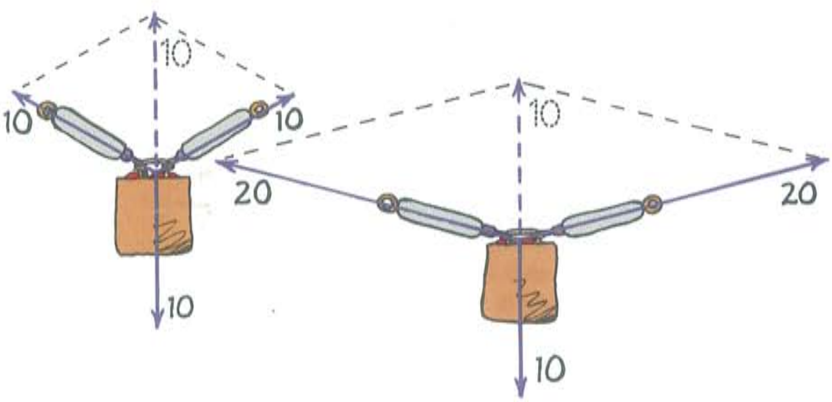


◄ Figure 4.14
As the angle between the spring scales increases, the scale readings increase to maintain the 10-N upward resultant. The 10-N resultant, shown as the dashed-line vector, is needed to support the 10-N load.

same, 10 N. If you understand this, you understand why a vertical clothesline can support your weight but a horizontal clothesline cannot. The tension in the nearly horizontal clothesline is much greater than the tension in the vertical clothesline, and therefore it breaks.

For any pair of scales, ropes, or wires supporting a load, the greater their angle from the vertical, the larger the tension force in them. The resultant of the tension forces, or the diagonal of the parallelogram they describe, must be equal and opposite to the load being supported. As you will see when you answer the following questions, the parallelogram technique of adding vectors yields some very interesting results.

Figure 4.15 ▶ You can safely hang from a vertically hanging clothesline, but you'll break the clothesline if it is strung horizontally.

Questions

1. If the kids on the swings are of equal weight, which swing is more likely to break?

2. Consider what would happen if you suspended a 10-N object midway along a very tight, horizontally stretched guitar string. Is it possible for the string to remain horizontal without a slight sag at the point of suspension?

Answers

1. The stretching force, or tension, is greater in the ropes hanging at an angle. The angled ropes are more likely to break than the vertical ropes.
2. No way! If the 10-N load is to hang in equilibrium, there must be a supporting 10-N upward resultant. The tension in each half of the guitar string must form a parallelogram with a vertically upward 10-N resultant. For a slight sag, the sides of the parallelogram are very, very long and the tension force is very large. To approach no sag is to approach an infinite tension. Turning this idea around, a little thought shows that pulling a tightly stretched string slightly to one side increases the tension in the string enormously. That's why a small sideways force can break a very strong guitar string!

4.9 The Moving Earth Again

Copernicus announced the idea of a moving earth in the sixteenth century. This controversial idea stimulated much argument and debate. One of the arguments against a moving earth was as follows. Consider a bird sitting at rest in the top of a tall tree. On the ground below is a fat, juicy worm. The bird sees the worm, drops down vertically, and catches it. It was argued that this would not be possible if the earth moved as Copernicus suggested. If Copernicus were correct, the earth would have to travel at a speed of 107 000 km/h to circle the sun in one year. Convert this speed to kilometers per second and you'll get 30 km/s. Even if the bird could descend from its branch in one second, the worm would have been swept away by the moving earth for a distance of 30 kilometers. For the bird to catch the worm under this circumstance would be an impossible task. The fact that birds do catch worms from high tree branches seemed to be clear evidence that the earth must be at rest.

Can you refute this argument? You can if you invoke the idea of inertia. You see, not only is the earth moving at 30 km/s, but so are the tree, the branch of the tree, the bird that sits on it, the worm below, and even the air in between. All are moving at 30 km/s. Things in motion remain in motion if no unbalanced forces act on them. So when the bird drops from the branch, its initial sideways motion of 30 km/s remains unchanged. It catches the worm and is quite unaffected by the motion of its total environment.

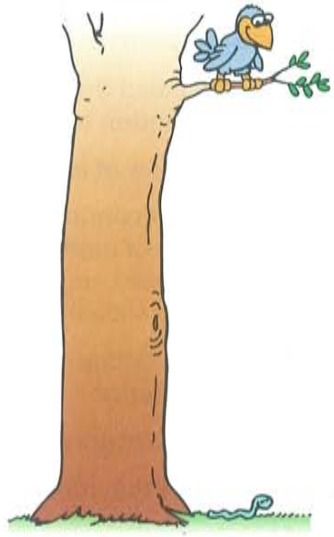


Figure 4.16 ▲
Must the earth be at rest for the bird to catch the worm?

Stand next to a wall. Jump up so that your feet no longer touch the floor. Does the 30-km/s wall slam into you? Why not? Because you are also traveling at 30 km/s, before, during, and after your jump. The 30 km/s is the speed of the earth relative to the sun, not the speed of the wall relative to you.

Four hundred years ago, people had difficulty with ideas like these, not only because they failed to acknowledge the concept of inertia, but also because they were not accustomed to moving in high-speed vehicles. Slow, bumpy rides in horse-drawn carriages do not lend themselves to experiments that reveal inertia. Today we flip a coin in a high-speed car, bus, or plane and catch the vertically moving coin as we would if the vehicle were at rest. We see evidence for the law of inertia when the horizontal motion of the coin before, during, and after the catch is the same. The coin keeps up with us. The vertical force of gravity affects only the vertical motion of the coin.

Figure 4.17 ▲
Flip a coin in a high-speed airplane, and it behaves as if the plane were at rest. The coin keeps up with you—inertia in action!

Our notions of motion today are very different from those of our distant ancestors. Aristotle did not recognize the idea of inertia, because he did not see that all moving things follow the same rules. He imagined different rules for motion in the heavens and motion on the earth. He saw horizontal motion as "unnatural," requiring a sustained force. Galileo and Newton, on the other hand, saw that all moving things follow the same rules. To them, moving things required *no* force to keep moving if friction was not present. We can only wonder how differently science might have progressed if Aristotle had recognized the unity of all kinds of motion and friction's effect on motion.

4 Chapter Review

For fuller explanations, see the TE notes in the front of this book.

Concept Summary

Galileo concluded that if it were not for friction, an object in motion would keep moving forever.

Newton's first law of motion—the law of inertia.

> Every object continues in a state of rest, or in a state of motion in a straight line at constant speed, unless it is compelled to change that state by forces exerted upon it.

Inertia is the resistance an object has to a change in its state of motion.

- Mass is a measure of inertia.
- Mass is not the same as volume.
- Mass is not the same as weight.
- The mass of an object depends only on the number and kind of atoms in it. Mass does not depend on the location of the object.
- The weight of an object is the gravitational force acting on it. Weight depends on the location of the object.

The net force, which is the vector sum of all forces acting on an object, affects the object's state of motion.

- When an object is at rest, its weight is balanced by an equal and opposite support force.
- An object is in equilibrium when it is at rest, with zero net force acting on it.

Important Terms

equilibrium (4.7)
force (4.3)
friction (4.3)
inertia (4.3)
kilogram (4.5)
law of inertia (4.4)
mass (4.5)
net force (4.6)
newton (4.5)
Newton's first law (4.4)
normal force (4.7)
support force (4.7)
weight (4.5)

Review Questions

Recall of key chapter ideas

1. What distinction did Aristotle make between natural motion and violent motion? (4.1)
   Natural, straight up or down; violent, imposed
2. Why was Copernicus reluctant to publish his ideas? (4.2) He feared persecution.
3. What is the effect of friction on a moving object? (4.3) Friction tends to slow a moving object.
4. The speed of a ball increases as it rolls down an incline and decreases as it rolls up an incline. What happens to its speed on a smooth, horizontal surface? (4.3) No change in speed horizontally (if no drag).
5. Galileo found that a ball rolling down one incline will pick up enough speed to roll up another. How high will it roll compared with its initial height? (4.3) To the same height if there's no friction
6. Does the law of inertia pertain to moving objects, objects at rest, or both? Support your answer with examples. (4.4) Both
7. The law of inertia states that no force is required to maintain motion. Why, then, do you have to keep peddling your bicycle to maintain motion? (4.4) To overcome friction
8. If you were in a spaceship and fired a cannonball into frictionless space, how much force would have to be exerted on the ball to keep it going? (4.4) None (a force is required to *change* motion).
9. Does a 2-kilogram rock have twice the mass of a 1-kilogram rock? Twice the inertia? Twice the weight (when weighed in the same location)? (4.5) Yes; yes; yes
10. Does a liter of molten lead have the same volume as a liter of apple juice? Does it have the same mass? (4.5) Yes; no
11. Why do physicists say mass is more fundamental than weight? (4.5) Mass is independent of location, whereas weight depends on the local gravity.

12. An elephant and a mouse would both have zero weight in gravity-free space. If they were moving toward you with the same speed, would they bump into you with the same effect? Explain. (4.5) The elephant is harder to stop—more inertia.

13. What is the weight of 2 kilograms of yogurt? (4.5) 19.6 N (rounded off, 20 N)

14. What is the net force or, equivalently, the resultant force acting on an object in equilibrium? (4.6) Zero

15. Forces of 10 N and 15 N in the same direction act on an object. What is the net force on the object? (4.6) 10 N + 15 N = 25 N

16. If forces of 10 N and 15 N act in opposite directions on an object, what is the net force? (4.6) 15 N − 10 N = 5 N

17. How does the tension in your arms compare when you let yourself dangle motionless by both arms and by one arm? (4.7) Tension is double with one arm.

18. A clothesline is under tension when you hang from it. Why is the tension greater when the clothesline is strung horizontally than when it hangs vertically? (4.8) Vert comps = wt, then big vectors along rope

19. If you hold a coin above your head while in a bus that is not moving, the coin will land at your feet when you drop it. Where will it land if the bus is moving in a straight line at constant speed? Explain. (4.9) At your feet, since no horiz acceleration

20. In the cabin of a jetliner that cruises at 600 km/h, a pillow drops from an overhead rack into your lap below. Since the jetliner is moving so fast, why doesn't the pillow slam into the rear of the compartment when it drops? What is the horizontal speed of the pillow relative to the ground? Relative to you inside the jetliner? (4.9) Horiz speed same as plane's; 600 km/h; zero

Plug and Chug

Math reinforcement—conceptual development through applied problem solving

1. If a woman has a mass of 50 kg, calculate her weight in newtons. Weight = *mg* = 50 kg × 9.8 N/kg = 490 N (500 N rounded)

2. Calculate in newtons the weight of a 2000-kg elephant. Weight = *mg* = 2000 kg × 9.8 N/kg = 19 600 N (20 000 N rounded)

3. Calculate in newtons the weight of a 2.5-kg melon. What is its weight in pounds? Weight = *mg* = 24.5 N; 5.5 lb

4. An apple weighs about 1 N. What is its mass in kilograms? What is its weight in pounds? *m* = 0.1 kg; weight = 0.22 lb

5. Susie Small finds she weighs 300 N. Calculate her mass. *m* = weight/*g* = (300 N)/(9.8 N/kg) = 30.6 kg (31 kg rounded)

Think and Explain

Conceptual development through applied critical thinking

1. Many automobile passengers suffer neck injuries when struck by cars from behind. How does Newton's law of inertia apply here? How do headrests help to guard against this type of injury? Whiplash, head tends to stay put as body moves forward; forces neck forward

2. Suppose you place a ball in the middle of a wagon and then accelerate the wagon forward. Describe the motion of the ball relative to (a) the ground and (b) the wagon. None rel to ground; backward rel to wagon

3. When a junked car is crushed into a compact cube, does its mass change? Its volume? Its weight? Mass same; volume less; weight same

4. If an elephant were chasing you, its enormous mass would be very threatening. But if you zigzagged, the elephant's mass would be to your advantage. Why? It's difficult for elephant to change its motion.

5. When you compress a sponge, which quantity changes: mass, inertia, volume, or weight? Only volume is changed.

6. A massive ball is suspended on a string and slowly pulled by another string attached to it from below, as shown in Figure A below.

   a. Is the string tension greater in the upper or the lower string? Which string is more likely to break? Which property, mass or weight, is important here? Upper; upper; weight

   b. If the string is instead snapped downward, which string is more likely to break? Is mass or weight important this time? Bottom; mass

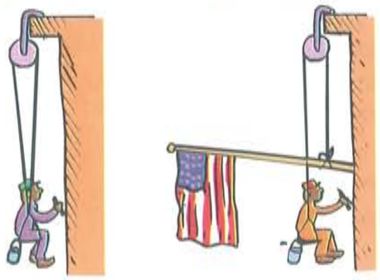
Figure A

Figure B

7. The head of a hammer is loose and you wish to tighten it by banging it against the top of a workbench. Why is it better to hold the hammer with the handle down, as shown in Figure B above, rather than with the head down? Explain in terms of inertia. Massive head tends to keep moving down.

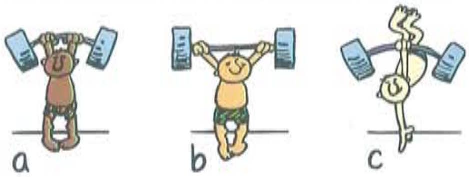
8. The little girl in the figure hangs at rest from the ends of the rope. How does the reading on the scale compare with her weight? Half (each strand supports half her weight).

9. Harry the painter swings year after year from his bosun's chair. His weight is 500 N and the rope, unknown to him, has a breaking point of 300 N. Why doesn't the rope break when he is supported as shown on the left? One day Harry is painting near a flagpole, and for a change, he ties the free end of the rope to the flagpole instead of to his chair (right). Why did Harry end up taking his vacation early? 2 ropes: 250 N each rope; 1 rope: 500 N



10. As the earth rotates about its axis, it takes three hours for the United States to pass beneath a point above the earth that is stationary relative to the sun. What is wrong with the following scheme? To travel from Washington D.C. to San Francisco using very little fuel, simply ascend in a helicopter high over Washington D.C. and wait three hours until San Francisco passes below. Helicopter's horiz speed is same as the earth's.

11. In which position is the tension the least in the arms of the weightlifter shown? The most? Least in *a;* most in *c,* in his bottom arm



12. Why can't the strong man pull hard enough to make the chain straight? Tension tends to infinity as angle nears 0°.

Think and Solve

Math reinforcement—variable substitution and equation solving

1. A medium-size American automobile has a weight of about 3000 pounds. What is its mass in kilograms? 3000 lb × 1 kg/2.2 lb = 1364 kg

2. If a woman weighs 500 N on Earth, what would she weigh on Jupiter, where the acceleration of gravity is 26 m/s²? Mass = (500 N)/(9.8 N/kg) = 51.02 kg, $W_{Jupiter} = mg$ = 51.02 kg × 26 N/kg = 1327 N (1300 N rounded)